

NASA'S SPACE LAUNCH SYSTEM:
A FLAGSHIP FOR EXPLORATION BEYOND EARTH'S ORBIT

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The National Aeronautics and Space Administration's (NASA) Space Launch System (SLS) Program, managed at the Marshall Space Flight Center, is making progress toward delivering a new capability for exploration beyond Earth orbit in an austere economic climate. This fact drives the SLS team to find innovative solutions to the challenges of designing, developing, fielding, and operating the largest rocket in history. To arrive at the current SLS plan, government and industry experts carefully analyzed hundreds of architecture options and arrived at the one clear solution to stringent requirements for safety, affordability, and sustainability over the decades that the rocket will be in operation. This paper will explore ways to fit this major development within the funding guidelines by using existing engine assets and hardware now in testing to meet a first launch by 2017. It will explain the SLS Program's long-range plan to keep the budget within bounds, yet evolve the 70 metric ton (t) initial lift capability to 130-t lift capability after the first two flights. To achieve the evolved configuration, advanced technologies must offer appropriate return on investment to be selected through a competitive process. For context, the SLS will be larger than the Saturn V that took 12 men on 6 trips for a total of 11 days on the lunar surface over 4 decades ago. Astronauts train for long-duration voyages on the International Space Station, but have not had transportation to go beyond Earth orbit in modern times, until now. NASA is refining its mission manifest, guided by U.S. Space Policy and the Global Exploration Roadmap. Launching the Orion Multi-Purpose Crew Vehicle's (MPCV's) first autonomous certification flight in 2017, followed by a crewed flight in 2021, the SLS will offer a robust way to transport international crews and the air, water, food, and equipment they need for extended trips to asteroids, Lagrange Points, and Mars. In addition, the SLS will accommodate high-priority science experiments. SLS affordability initiatives include streamlining interfaces, applying risk-based insight into contracted work, centralizing systems engineering and integration, and nurturing a learning culture that continually benchmarks its performance against successful ventures. As this paper will explain, the SLS is making measurable progress toward becoming a global infrastructure asset for robotic and human scouts of all nations by harnessing business and technological innovations to deliver sustainable solutions for space exploration.

I. INTRODUCTION

The SLS rocket will support missions of international importance as the first exploration-class launch vehicle flown by the United States (U.S.) since the Apollo Program's Saturn V. Continuing the tradition of America's first 50 years in space, this new heavy-lift rocket will provide the sheer power and payload capacity needed to overcome limitations that have until now delayed humanity's voyage of discovery in the solar system (Fig. I). The SLS offers game-changing possibilities for economic vitality in space and on Earth, safely transporting astronauts to unexplored regions in search of knowledge and delivering cutting-edge missions that will rewrite scientific texts and spur technological advances.

NASA has set a steady course to resume human space flight by integrating the SLS Program at Marshall Space Flight Center, the Orion MPCV Program at Johnson Space Center, and the Ground Systems Development and Operations (GSDO) Program at Kennedy Space Center. Together, they offer the potential for social and economic benefits characteristic of U.S. infrastructure initiatives that

were successfully carried out in years past, thanks to governmental oversight and funding. Examples include the Hoover Dam, which enabled arid western lands to be transformed into thriving cities, and the Interstate Highway System, which opened the country to huge waves of commercial expansion before it was even completed.



Fig. I: Advancing human space exploration – Saturn V, Space Shuttle, and Space Launch System.

The SLS rocket is central to NASA's capability-driven framework, designed to launch planetary probes and great astronomical observatories, enable the human/robotic interface to be synchronized, and make preparations to set the first astronaut's boot prints on Mars. It will be associated with surprising new innovations, some in response to paradigm-changing discoveries, others to improve existing methods for recycling waste, obtaining clean water, and harnessing alternative energy sources — like solar power — in practical and affordable ways. International partners will be invited to participate in missions to foster the peaceful pursuit of mutual objectives on the space frontier, as outlined in the

Global Exploration Roadmap (September 2011) and *The National Space Policy of the United States of America* (June 2010).^{*,†}

This new infrastructure asset is positioned for success. The SLS concept and management plan are the result of careful deliberations and years of study within NASA and other U.S. Government agencies, including the Office of Science and Technology Policy and the Office of Management and Budget, as well as in consultation with internal and external stakeholders. Detailed and independently verified engineering and business analyses support the vehicle architecture and strategy to get to first flight by 2017 (Fig. II).

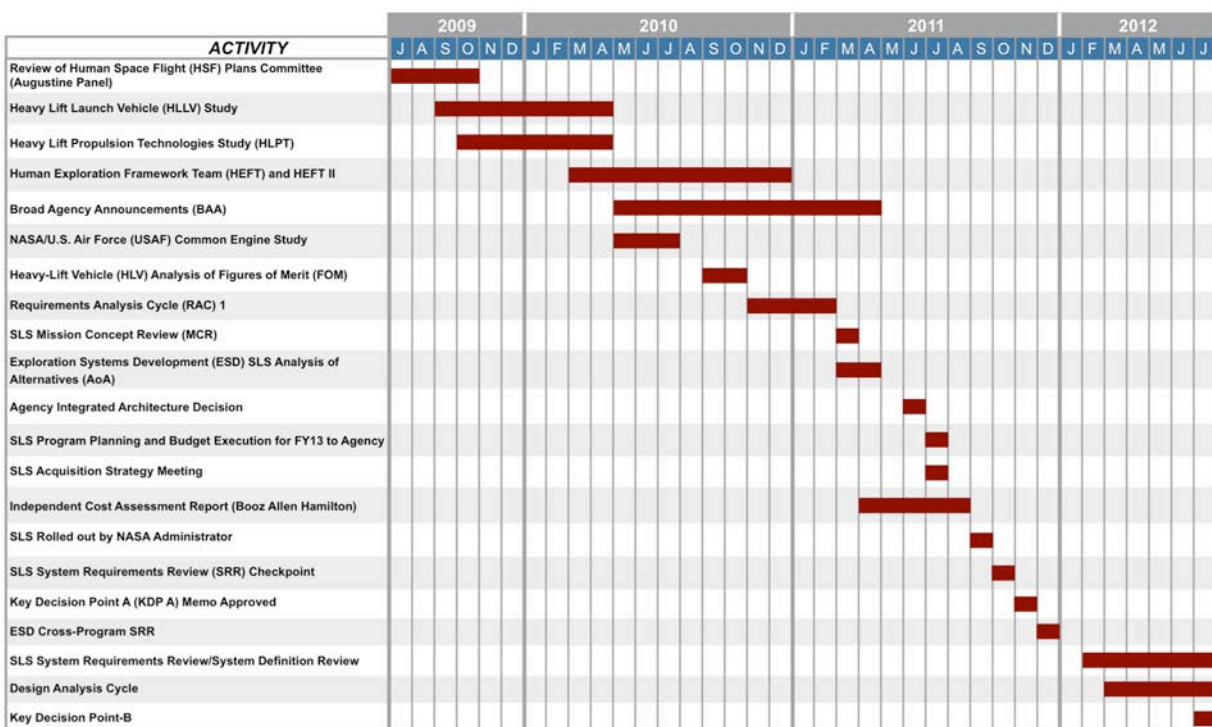


Fig. II. Careful planning and deliberations are helping the SLS Program meet its commitments.

* International Space Exploration Coordination Group. (2011, Sep.). *The Global Exploration Roadmap*. [Online]. Available: http://www.nasa.gov/pdf/591067main_GER_2011_small_single.pdf

† The White House. (2010, Jun. 28). *National Space Policy of the United States of America*. [Online]. Available: http://www.whitehouse.gov/sites/default/files/national_space_policy_6-28-10.pdf

Building the most capable U.S. rocket is a commitment of limited resources, especially when accepting the challenge of a first flight in five years. NASA selected the SLS architecture to leverage existing engines in NASA's inventory and complete propulsion hardware now well into the development phase. This option is not only the most cost-effective choice — it also offers unprecedented performance.

The SLS management approach incorporates the best practices of lean organizations to deliver a safe, affordable, and sustainable solution. In the year since the SLS Program was announced, the team has completed NASA's System Requirements Review and System Definition Review (SRR/SDR) and steady progress is being made toward the next major milestone — the Preliminary Design Review in 2013.

II. ARCHITECTURE OVERVIEW AND ACCOMPLISHMENTS

After studying priority stakeholder requirements, NASA selected a design that provides a platform for international cooperation in space while supporting new options and destinations not considered possible until now, opening the potential for technological achievements, high-value science missions, and expanding the global economy. Many commercial rockets are available in the medium-to-heavy class, but super-heavy-lift vehicles like SLS lie solely within the Government's purview, due to the investment required for fielding an entirely new infrastructure asset for scientific exploration beyond Earth's orbit (Fig. III).

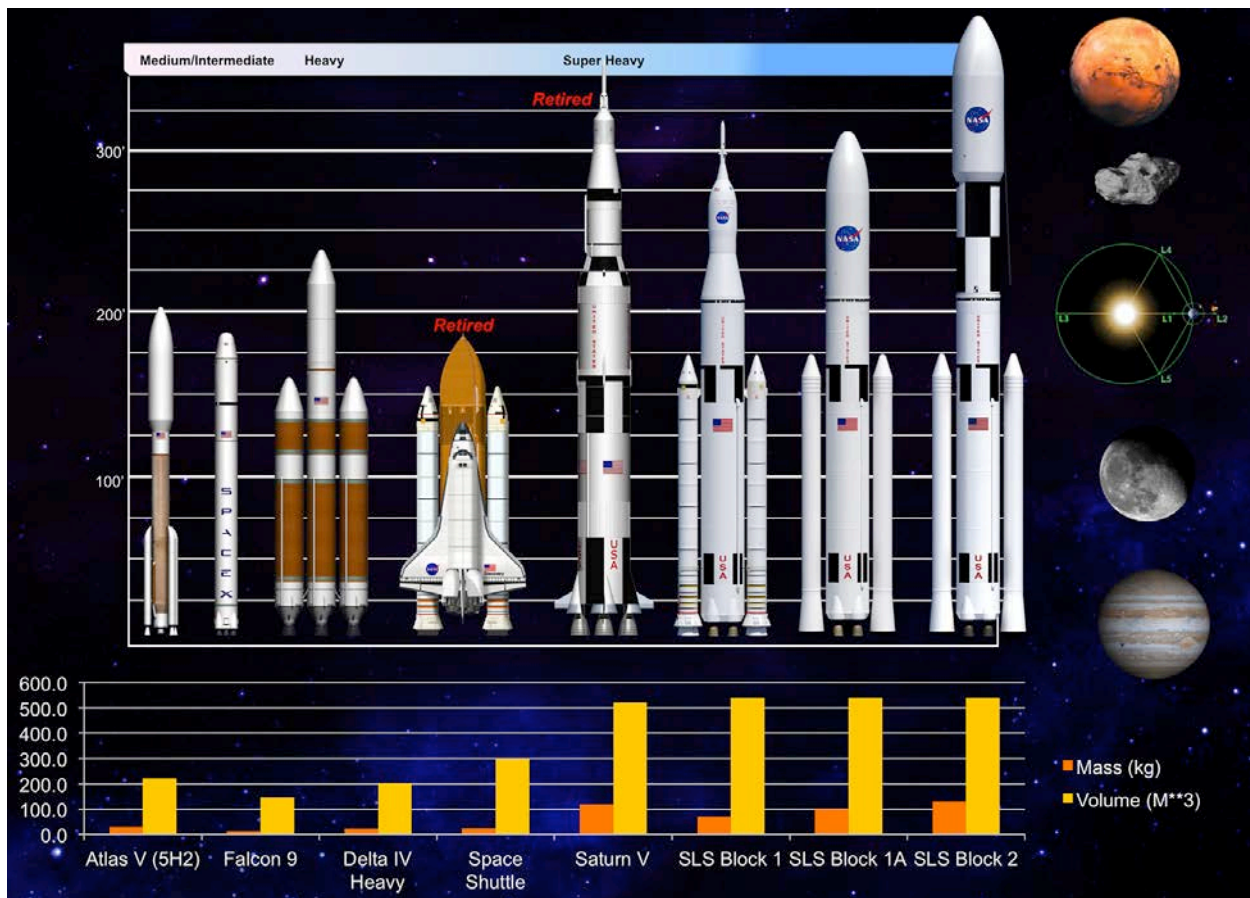


Fig. III: SLS scale relative to other U.S. systems.

The NASA Authorization Act of 2010 directs NASA to develop the SLS rocket as a follow-on to the Space Shuttle, with the capability of accessing cis-lunar space and regions beyond low-Earth orbit (LEO), in order to allow the U.S. to participate in global efforts to develop this increasingly strategic region.[†] The Act also provides a series of minimum capabilities. The SLS vehicle must be able to: (a) lift 70 t to LEO initially and then be evolvable to lift 130 t or more, (b) lift the Orion spacecraft, and (c) serve as a backup system for delivering cargo and crew to the International Space Station, in the event that such requirements cannot be met by available commercial or partner-supplied vehicles. These top-level requirements drive technical trade studies and resource planning, as the SLS concept is refined to address design reference missions to destinations such as geosynchronous-Earth orbit and high-Earth orbit, along with figures of merit for safety, affordability, and reliability.

As part of its affordability tenets and design strategy, the SLS core and upper stages share important common attributes—such as outer diameter, material composition, subsystem components, and tooling—that allow NASA to capitalize on these synergies. The SLS stages and other hardware will be designed once and used many times in keeping with the Program’s affordability strategy (Fig. IV).

The rocket’s initial Block 1 design includes a 27.5-ft (8.4-m) core stage tank that delivers liquid oxygen/liquid hydrogen (LOX/LH₂) propellant to four RS-25 engines (Fig. V). This configuration will support the first 4 missions, with 16 engines now in inventory, taking advantage of 30 years of U.S. experience with LOX/LH₂, as well as an existing national infrastructure that includes specialized manufacturing and launching facilities.[§] To take advantage of synergies between the core stage engine and the upper stage engine discussed below, a common controller is being developed that will work for both variants.

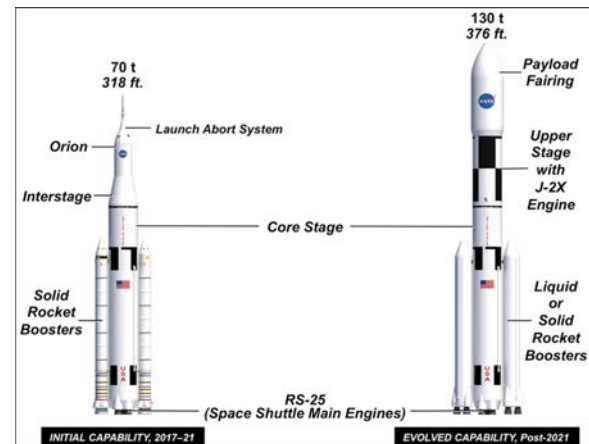


Fig. IV. Flexible, modular evolution through planned block upgrades.

LOX/LH₂ is also used by the J-2X upper stage engine, now in the testing phase, which will support future performance requirements as the SLS rocket evolves through planned block upgrades (Fig. VI). The J-2X engine is an advanced version of the J-2 upper stage engine developed for the Saturn V launch vehicles. It is designed to start and restart in orbit, generating approximately 294,000 lbs. (1,308 kN) of thrust to LEO or 242,000 lbs. (1,076 kN) of thrust from LEO into deep space.^{<¶}

The initial SLS rocket will use the world’s most powerful solid rocket boosters (SRBs), now in development (Fig. VII). During launch, each solid rocket motor will generate up to 3,600,000 lbs. (16,013,598 kN) of thrust. Although similar to the SRBs used on the Space Shuttle, this upgraded 5-segment SRB includes improvements such as a larger nozzle throat and an environmentally benign insulation and liner.^{**}

[†] 111th Congress. (2010, Oct. 11). *Public Law 267: NASA Authorization Act of 2010*. [Online]. Available: <http://www.gpo.gov/fdsys/pkg/PLAW-111publ267/html/PLAW-111publ267.htm>

[§] National Aeronautics and Space Administration. (2011). Space Launch System. [Online]. Available: www.nasa.gov/sls

^{<¶} National Aeronautics and Space Administration. (2011, Jul. 14). “NASA Begins Testing of Next-Generation J-2X Rocket Engine.” [Online.] Available: http://www.nasa.gov/mission_pages/j2x/j2x_ignition.html

^{**} National Aeronautics and Space Administration. (2011, Sep. 8). “NASA Successfully Tests Five-Segment Solid Rocket Motor.” [Online.] Available: www.nasa.gov/exploration/features/dm3.html



Fig. V: RS-25 core stage engines in inventory.



Fig. VI: J-2X upper stage engine testing.



Fig. VII: A 5-segment booster development test.

The evolved Block 2 SLS rocket will need even more advanced boosters, ones that exceed the limits of today's technology. This requirement provides a competitive opportunity for industry to deliver cost-effective, innovative hardware for deep-space missions to be conducted after 2021. The engineering demonstration and risk-reduction phase will begin in 2012, to be followed later by full-and-open competition for design, development, test, and evaluation (DDT&E).^{tt}

^{tt} National Aeronautics and Space Administration. (2011, Sep. 23). "NASA to Brief Industry on Space Launch System Procurement." [Online.] Available: http://www.nasa.gov/home/hqnews/2011/sep/HQ_M11-204_MSFC_Indust_Day.html

After considering hundreds of possibilities for the SLS rocket, NASA ultimately selected the one design that came closest to meeting system-level requirements while fitting into a well-defined annual budget with no planned escalations. These objectives are supported by the rocket's relatively simple design, which uses a minimal number of hardware elements to achieve the desired performance, as well as building the initial SLS rocket from existing hardware assets and other elements already well into development.

This strategy is integral to trade studies conducted during design analysis cycles. In its trade studies, the SLS Program considers production and operations (P&O) costs as independent variables, along with nonrecurring development costs. Plans nominally call for one mission per year, which makes any additional missions more affordable.

The rocket's modular and flexible design can be: (a) outfitted with a cargo fairing to enclose flagship science instruments and experiments or (b) configured for the Orion spacecraft and associated equipment. The latter will provide emergency abort capability, protect and sustain the crew during the mission, and enable safe reentry from deep space at high velocities.^{tt}

Design and development activities are being conducted concurrently to save time and money. For example, the first SRB qualification motor is being prepared for static-testing in 2013 (Fig. VIII).^{*} As part of the contractor's affordability initiative, it has performed process value-stream mapping, resulting in significant cost savings by reducing unnecessary manufacturing steps. Taken together, individual savings add up to significant cost containment.

^{tt} National Aeronautics and Space Administration. (2011). Explore the Exploration Vehicle. [Online.] Available: <http://www.nasa.gov/exploration/systems/mpcv/explore.html>

^{*} National Aeronautics and Space Administration. (2012, Jul.). "Casting Begins for Booster QM-1." *SLS Highlights*. [Online.] Available: http://www.nasa.gov/exploration/systems/sls/sls_highlights.html



Fig. VIII. Booster qualification motor casting.

As another example of measurable progress, the SLS avionics team is fine-tuning flight software, using test-bed computers received ahead of schedule (Fig. IX). Availability of the platform early in the engineering development phase allows NASA programmers more time to develop the most capable flight software in history. Existing systems from communications and Global Positioning System (GPS) satellites are being upgraded to provide the highest processing capability available.[†]



Fig. IX. SLS avionics software testing.

As part of its lean systems engineering and integration effort, NASA also has completed early wind tunnel testing for the SLS rocket, which helps ensure that it presents an affordable and sustainable

backbone for long-term human space exploration (Fig. X). SLS concepts are being thoroughly tested in wind tunnels, where scale models are used to evaluate the design's performance. Any necessary changes can then be made safely, easily, and inexpensively before the full-scale vehicle is built.[†]



Fig. X. Over 900 SLS wind-tunnel tests have been conducted.

As a final example of progress over the SLS Program's first year, the Multi-Purpose Crew Vehicle Stage Adapter (MSA) has gone from design drawing to manufacturing in a matter of months. This hardware, which will mate the Orion test article to the Delta IV rocket on a low-Earth orbit flight in 2014, will also be used for the full-up autonomous Orion on the SLS rocket's maiden voyage in 2017. Again, the philosophy of design once and use many times reflects the Program's commitment to affordability and a modular, flexible approach to mission support.

III. ONE ROCKET, MANY MISSIONS

As stated above, the initial SLS rocket will carry the Orion spacecraft during an autonomous demonstration flight in 2017, as well as a crewed mission in 2021, which will be the first time that astronauts have gone beyond Earth's orbit in over 40 years.

President Obama has challenged NASA to send humans to a near-Earth asteroid by 2025 and to Mars in the 2030's. NASA has made exciting discoveries about the Red Planet, with the help of Mars rovers *Opportunity* and *Spirit*. Scientists have confirmed the

[†] National Aeronautics and Space Administration. (2012, May). "Flight Computer Testbed Received at Marshall." *SLS Highlights*. [Online.] Available: http://www.nasa.gov/exploration/systems/sls/sls_highlights.html.

[†] National Aeronautics and Space Administration. (2012, Jul.). "SLS Completes Early Wind Tunnel Testing." *SLS Highlights*. [Online.] Available: http://www.nasa.gov/exploration/systems/sls/sls_highlights.html

seasonal presence of saltwater there, using data obtained by the *Mars Reconnaissance Orbiter*.[§] The Mars Science Laboratory, known as *Curiosity*, is a precursor to human landings on the planet most like Earth. For scientists, the performance offered by the SLS rocket will be available to launch decadal-class missions to Jupiter's icy moons, the rings of Saturn, and other high-value destinations.

Currently, NASA is conducting mission concept and operations studies in conjunction with stakeholders and partners. The results of these studies will be the subject of future papers and forums.

IV. MANAGEMENT APPROACH, PLANS, AND PROGRESS

Space flight always presents serious challenges and, as former Space Shuttle Program Manager Wayne Hale reminds managers and rocket scientists alike: "This enterprise is not for the faint of heart."^{<Jl} As the SLS concept moves quickly from the digital drawing board to the launch pad at the Kennedy Space Center, designers and operators are working together to maximize the American taxpayer's investment in this unprecedented capability (Fig. XI).



Fig. XI: SLS on the launch pad (artist's concept).

NASA is fitting human exploration into a budget that is less than that of the Space Shuttle Program, even though the SLS rocket offers more capability than a Saturn V. One of the greatest challenges is determining how to reduce recurring and fixed

operating costs. Every development activity represents a chance to calibrate the team in keeping with the current economic environment and create sweeping cultural changes to ensure sustainability.

The SLS Program's management approach engages the existing industrial base, including the workforce's critical skills and talent. SLS content must be executed well within its funding, based upon many lessons learned over the last few decades of human space flight. The first priority is safety, followed closely by affordability. The SLS team is using best practices from industry and Government to reduce the rocket's time to market and total DDT&E investment. Straightforward lean principles have been implemented, with a healthy dose of forward-leaning competitive opportunities, which will spur innovation and drive efficiencies into the system.

The aerospace professionals who have signed on for the SLS Program bring diverse and wide-ranging backgrounds to the table. They are well-prepared and eager for the opportunity to fly a new generation of missions on a rocket that can take explorers and scientists anywhere that they can imagine. The expectation is set for system optimization, using business and engineering solutions that give the best return on investment, both in terms of up-front nonrecurring costs and long-term sustainability. This team is product-centric — focused on building and flying hardware — and that product is the SLS rocket. All processes and documentation must add value toward delivering it.

Affordability is a key performance factor against which success is measured. Many variables are being aligned as NASA carefully considers P&O costs in tandem with DDT&E activities while employing modern manufacturing and vehicle processing techniques, implementing risk-based insight/oversight practices, and streamlining contractor deliverables. Taken together, some very simple improvements can add up to substantial savings. The SLS Affordability Plan lays out detailed steps for cost-cutting actions such as scaling back the number of management boards used to control the vehicle configuration, allowing correct decisions to be made more quickly. Formal contractor deliverables are being significantly reduced. Fewer Category 1 deliverables (which must be approved by the Government) are required, with additional savings being realized on production and reproduction costs by accepting electronic documents in the contractor's preferred format.

NASA selected this vehicle configuration based upon technical and business trade studies informed by a certain philosophy and set of assumptions. The primary figure of merit was cost, both for the Government requirements analysis cycle (RAC)

[§] National Aeronautics and Space Administration. (2011, Aug. 4). "Salt Water May Flow on Mars." [Online.] Available: http://science.nasa.gov/science-news/science-at-nasa/2011/04aug_marsflows/

^{<Jl} Wayne Hale. (2011, Sep. 20). "The School of Hard Knocks." [Online.] Available: <http://waynehale.wordpress.com/2011/09/20/the-school-of-hard-knocks/>

teams and 13 prime-contractor companies that provided input through the Heavy Lift Propulsion Technologies Broad Agency Announcement (BAA) processes. A technical interchange meeting was held with industry to further refine insight/oversight suggestions from the requirements analysis cycle and BAA process. Even now, SLS team members are benchmarking against profitable companies that employ design-to-cost practices.

Affordability is an overarching driver within NASA's transformational paradigm. Early flight capability with significant DDT&E and P&O cost savings can be realized through existing manufacturing and launch-site infrastructure, as well as employing proven heritage hardware. Design commonality and manufacturing receive heavy emphasis, as do simplicity of processing and launch operations, allowing a flat budget to be maintained throughout the DDT&E process and in years to come. These design-to-cost goals require the team to adopt a mission-oriented battleship mentality, driving its decisions towards rugged and robust system design. "Bells and whistles" design is being supplanted by more utilitarian and service-oriented selections that provide adequate margin to trade performance for cost. This strategy helps streamline one of the biggest expenses in a developmental program – the decision-making process – as does holding budget reserves at the lowest levels possible.

A new culture is emerging, with a general revectoring to ensure that processes support product development instead of the other way around. The expectation is being clearly and consistently articulated that cost is a variable over which the team must exercise judicious control. Cross-validation has been provided by the RAC and BAA studies in many ways. Affordability FOM analyses helped infuse this mandate into the SLS Concept of Operations, as well as the very fiber of the organization, by generating both general and specific recommendations to be addressed early in the SLS Program's life-cycle.

SLS managers reduce risk in many ways. Both performance margin and budget reserves are being held to address the unknowns that inevitably accompany engineering feats of this magnitude. The SLS Program will affordably deliver a 70-t lift capability in the near term by managing cost and mass in similar ways.

Over the years, NASA has contributed much to the world's engineering and scientific literature, including launch vehicle studies and plans. Now the Agency is putting a plan into action that can effectively take advantage of opportunities for affordability (Fig. XII). The SLS Program serves as a foundational capability for designing in efficiencies on the front end, in order to support a positive balance sheet during the operations phase.

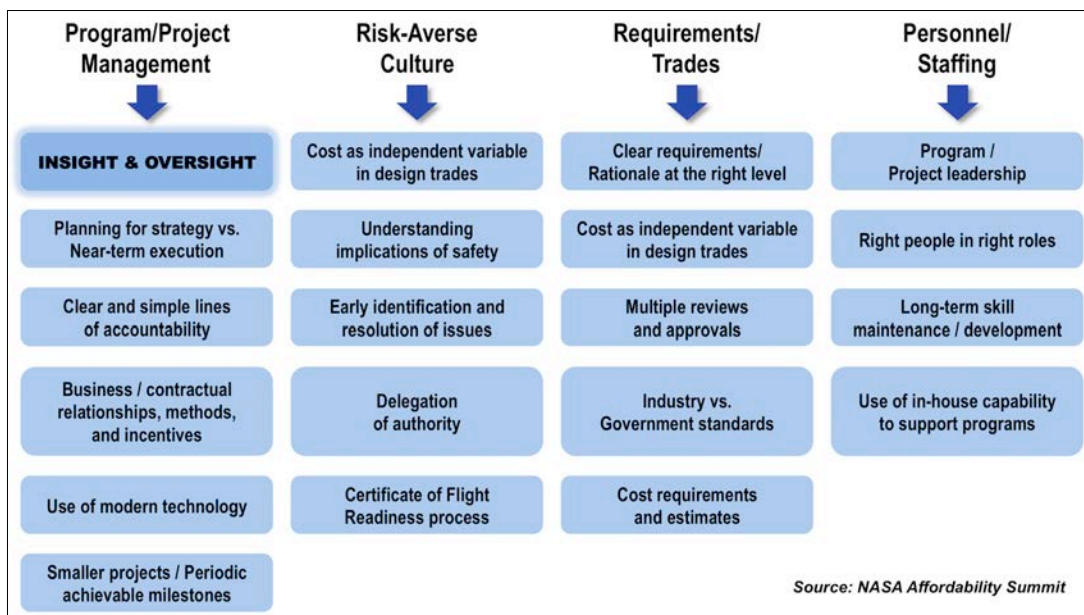


Fig. XII: Pursuing opportunities for affordability.

The SLS team includes some of the world's top rocket scientists, who are finding new solutions to longstanding challenges. Each day, these lean principles and practices and industry best practices are being lived by a team dedicated to doing the right thing by driving affordability into the very design of the SLS rocket. They are well aware that as much as 80 percent of fixed costs are set during the design phase and that designing to cost is one variable over which the team has total control. The team has logged many accomplishments, which include meeting decision-gates as the Program moves through formulation into the implementation phase.

NASA announced the SLS Program on September 14, 2011. In just 1 year, the Program is now performing preliminary design and technology completion phase, with a clear path to first flight (Table I). Plans are being made with partner programs Orion and GSDO through NASA's Human Exploration and Operations Mission Directorate, to deliver a next-generation human space flight system to continue the journey of discovery that is well underway. The rocket has performance margin to spare, while the Program holds sufficient budget reserves to address the unexpected challenges that will surely arise during an endeavor of such magnitude and complexity. Building and flying this rocket will be one of the most demanding jobs on the planet, one that can only be performed by those who can deliver paradigm-changing capabilities to launch a new day in space.

Activity	Date
SRR/SDR	July 2012
Preliminary Design Review	2013
Critical Design Review	2015
Design Certification Review	2016
First Flight: Orion Autonomous	
Beyond-Earth Orbit Mission	December 2017

Table I: Selected SLS life-cycle milestones.

V. CONCLUSIONS

NASA's new SLS rocket represents the most practical and affordable course of action for leaving Earth orbit at this time. Far-reaching ramifications are being set into motion as a sound technical climate and potential mission manifest are created for sustainable exploration. The SLS rocket has been validated by numerous internal and external stakeholder organizations, and it is supported by the Agency's 2011 Strategic Plan. It will fly carefully selected flagship missions defined by distinguished organizations such as the National Research Council

and the International Space Exploration Coordination Group. New knowledge and understanding will be gained about the universe in which we live, allowing the entire world to rewrite standard references, develop advanced technologies, and undertake new economic initiatives (Fig. XIII).



Fig. XIII: The SLS rocket will launch in 2017 (artist's concept).

NASA selected the SLS rocket as its next human-rated heavy-lift launch vehicle because this design offers the optimum solution for exploring with astronauts – who are capable of much greater initiative and insight than robotic probes, valuable though they may be – to safely, cost-effectively, and quickly resume the exploration of our solar system in the current economic climate. SLS team members will stay focused on their ultimate product, the rocket, as its design matures through upcoming life-cycle reviews. The SLS Program's planning strategy includes the use of hardware that already exists or is close to completion, as well as appropriately incorporating advanced technologies that offer attractive return on investment to support NASA's affordability goals. The SLS rocket's design is flexible and evolvable. It provides incremental stakeholder value by fielding an initial capability successively refined in line with budget realities and the evolving plans of partner coalitions.

NASA's vision is "To reach for new heights and reveal the unknown, so that what we do and learn will benefit all humankind," and the first plank in its strategic goals is to "Extend and sustain human activities across the solar system."^{**} The SLS rocket offers a realistic and sturdy backbone for taking the next step out into the cosmic neighborhood that is our home. The SLS Program and its partners are dedicated to meeting their commitments and doing things differently for the right reasons, in the process creating an entirely new capability to directly support human space flight beyond Earth's orbit. Ultimately, this approach will reduce the risk of undertaking a new slate of science and exploration missions, sending launch vehicles and their payloads into new regions, freeing the imagination to open the frontiers of scientific intelligence and technological advancement, which ultimately benefits the citizens of planet Earth.

^{**} National Aeronautics and Space Administration. (2011: Feb. 14). *2011 NASA Strategic Plan*. [Online.] Available: http://www.nasa.gov/pdf/516579main_NASA2011StrategicPlan.pdf